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Assessment of renewable energy resources potential for large scale and standalone applications in Ethiopia

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ABSTRACT

This study aims to determine the contribution of renewable energy to large scale and standalone application in Ethiopia. The assessment starts by determining the present energy system and the available potentials. Subsequently, the contribution of the available potentials for large scale and standalone applications are determined taking into account the present energy system. The present energy system shows a large variation between urban and rural consumption. Almost all rural households depend on traditional biomass-based energy for cooking, while about 90% of urban households use electricity for lighting. The current national energy consumption from petroleum and electricity only accounts for 7% of the total energy demand; implying the largest energy need for cooking. The current annual Ethiopian household's energy demand for cooking is ten times as large as the household use for cooking in western countries. About 90% of the energy is lost to the ambient air as a result of the inefficient conversion system during cooking. However, the country has an annual exploitable electric energy potential of 7.5 PWh from solar energy, 4 PWh from wind energy and 0.2 PWh from hydroelectric energy. These renewable sources can supply enough energy to fulfill the demand; however, the energy carrier (electricity) is not appropriate for heating/cooking food, since cooking appliances on electricity are expensive in rural areas. While renewable energy sources can fulfill energy needs at a national scale, they are not at all suitable for fulfilling energy needs in rural areas except lighting and some elementary services. Therefore prevailing western approaches to renewable energy supply systems do not solve energy problems in developing countries. This shows the urgent need for addressing the energy demand for cooking.

Contents

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1. Introduction

Energy is vital to any economic development, to improve societal comfort and wellbeing [1]. Fast economic growth and social transition in western countries are directly attributed to progressive invention and improvement of modern energy services [2]. Currently fossil fuel accounts for more than 90% of overall energy supply of western countries resulting in their share of 80% of the global fossil fuel energy consumption. However, since the mid-20th century, the concern over diminishing reserves of fossil fuel and greenhouse gas emissions arose as new global environmental challenges [3]. The poorest countries in the world were unable to benefit from the cheap fossil fuel era and the associated modern energy services. About 45% of those deprived of modern energy services are living in Sub-Saharan African countries where traditional biomass accounts for more than 90% of their overall energy uses [4]. Biomass is a carbon neutral renewable source based on photosynthesis. Its current use though is associated with burning in inefficient stoves, possibly leading to scarcity of firewood, deforestation and impaired health. Fossil fuel is less likely to provide a solution for poor countries relying on foreign oil imports due to its surging prices and related greenhouse gas emissions. Renewable energy sources are the only viable option to be developed.

Renewable energy sources such as hydro, wind and solar energy are promising options for the energy and environmental challenges the world is facing today. The possible share of renewable energy in the global electricity production increases as the price of conventional fossil fuels tends to increase [5]. However, their spatial and temporal availability and technological developments determines to what extent renewables can contribute. A number of studies have been made to determine their global production potentials at different categories [6,7]. These categories are made to indicate the extent to which renewable energies are theoretically, technically and economically available to be exploited [7,8]. In western countries the available energy infrastructure allows relatively easy incorporation of renewable energy into the system, whereas this is less likely to occur in Africa with its poor energy infrastructure. Only few studies have attempted to assess the renewable energy potentials of Ethiopia [9,10]. These studies emphasized on the temporal–spatial variation of the country's solar and wind energy resources. Two studies [11,12] determined the feasibility of renewable resources in a small scale hybrid electric system. None of the studies has yet determined its magnitude at different scales of potentials and contribution to the country's energy system. Estimation of the potential at different scales is essential to stimulate investors and energy planners working in the energy sector. In Ethiopia 83% of the population lives in rural areas are unconnected to the grid. Connecting them to the grid soon is less likely since they are sparsely distributed. Hence, the level to which available renewable energy potentials can solve the issue of the energy supply for cooking needs to be determined prior to any development plan. It is also important to consider the potential for large scale application since the country is among the non-domestic oil and gas producing African countries where renewable energy is required to support the economy. The economic analysis of the renewable energy sources is not included in current study only its technical suitability is considered taking into account rural developing country's living situations.

In this research hydro, solar and wind energy are among the renewable energy sources selected for the assessment. In Section 2, the present energy system is reviewed by making a clear distinction between rural and urban areas. Section 3 deals with the description of data sources and specific methods used for the estimation of the potentials for renewable energy sources. In Section 4, the findings from the assessments are presented. The contribution of available potentials to large scale grid and standalone applications are discussed and determined in Section 5, and finally concluding remark is forwarded in the last section. Emphasis is given to standalone applications, since a large part of the population lives in rural areas is not connected to the grid. The results of the assessment are used to answer the question to which extent electricity from renewable energy sources can help to alleviate rural cooking energy problems as well as to contribute to large scale grid system. Because considered renewable energy

Table 1
Main statistical indicators of Ethiopia.

Indicator	Unit	2005	2006	2007	2008	2009	2010	2011
Population	Million	74	76	78	79	81	83	85
Rural population	%	84	84	84	84	83	83	83
GDP (constant 2005 US$)	$billion	12	14	15	17	18	20	21
Annual GDP growth	%	11.8	10.8	11.4	10.7	8.8	9.9	7.3
Per capita GDP (cont. 2005 US$)	$USD	160	172	187	202	214	229	240
Electricity production	TWh	2.9	3.3	3.6	3.8	4.0	5.0	6.3
Per capita electric consumption	kWh	34	39	41	43	45	54	75
Per capita energy use	kgoe	380	379	380	381	382	382	381

Source [13].

sources are used for the production of electricity, but their contribution to grid and standalone application might be different.

1.1. Background of the country

Ethiopia is located in the horn of Africa between 3 and 15 degrees northern latitude and 33 and 48 degrees eastern longitude covering a land area of about one million square kilometers. Ethiopia has a population of about 83 million, of which 83% lives in rural areas. Ethiopia is a highland country with 65% of its total area at an elevation of more than 1400 m above sea level with some low land areas extending up to 120 m below sea level. The Great Rift Valley divides the country into two parts at the central highlands. The altitude goes on decreasing from the center outwards in almost all directions. Ethiopia has a diversified climate ranging from a semi-arid desert type in the lowlands to a humid and warm (temperate) type in the southwest. Mean annual rainfall distribution exceeds 2000 mm over the South-western highlands and is below 300 mm over the south-eastern and North-eastern lowlands. There is no clear distinction between seasons in Ethiopia, but based on rainfall, December to February are categorized as the dry season and June to August as the wet season. Since 2004, the country has achieved about 10% annual GDP growth. The growth in energy sector particularly with a conventional installed electricity capacity of hydro is also remarkable although rural energy poverty still remains an issue. Some of the key statistical indicators of the country are presented in Table 1.

2. Current primary energy consumption in Ethiopia

Primary energy consumption refers to direct energy use at the source without transformation or conversion processes. The primary energy consumption data is retrieved from the ministry of water resources and energy, Ethiopian electric power corporation and IEA national statistics databases [14–16]. The Ethiopian primary energy consumption predominantly derived from biomass accounts for about 91% of the total energy consumption. The biomass is obtained from forests, agricultural areas and from animal wastes. Petroleum accounts for about 7% of the total consumption imported at the expense of huge foreign exchanges. Electric energy accounts for only 2%, which is mainly used for urban household consumption and industrial purposes. Most of the electric energy is obtained from the national grid generated by hydropower. Only villages and towns with access to grid system are benefiting from the electricity system. The majority of the rural households is not connected to the grid and is not able to benefit from the electricity supply system. Now-a-days there is a growing interest to use standalone diesel generators and solar PV system to bridge the gap. Fig. 1a shows the primary energy consumption of the sectors. Therefore, about 93% of the total energy is used by households, followed by transportation (5%), industry and services share 1% each. Commercial energy use for agriculture is negligible due to a subsistent agricultural system operated by animal and human power.

2.1. Energy consumption by fuel types

This paper distinguishes the type and amount of energy consumed based on the data taken from international energy agency (IEA) statistics, Ministry of water and energy of Ethiopia database and Ethiopian electric power corporation (EEPCo) [14–16]. EEPCo is the only government owned electric utility in the country responsible for electric energy production and distribution. Data on biomass fuel and petroleum product, available in heat energy units in Joule, is converted to electric heat unit in kilowatt-hour (1 kWh = 3.6 MJ), in order to make the fuels comparable. Fig. 1b presents the country's primary energy consumption by fuel types. Biomass, petroleum and electricity are the main energy carrier accounting for 92%, 7% and 1%, respectively.

2.1.1. Biomass

In Ethiopia biomass is the main energy source used in all economic sectors. It accounts for 334 TWh (= 10^{12} Wh) out of 365 TWh of the total primary energy consumption, equivalent to 20 MWh per household per year. More than 98% of the rural households use firewood, crops residues/leaves and cows dung for cooking [17]. Dissemination of improved cooking stove is very low or almost nil in rural areas, therefore, most of the biomass is used in traditional stoves. The prominent traditional stove used for cooking in rural and poor urban household is a three stone open fire. Such kind of stove has a conversion efficiency of about 10% [18]. Thus, the annual household use is estimated to be

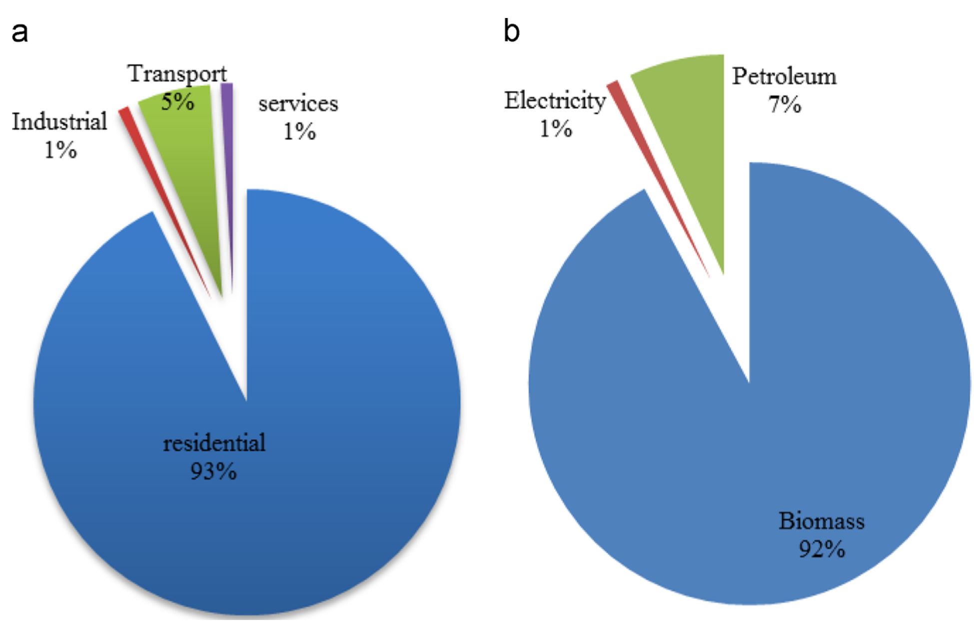

Fig. 1. (a) Energy consumption by sector and (b) energy consumption by fuel type in 2011 [15,16].

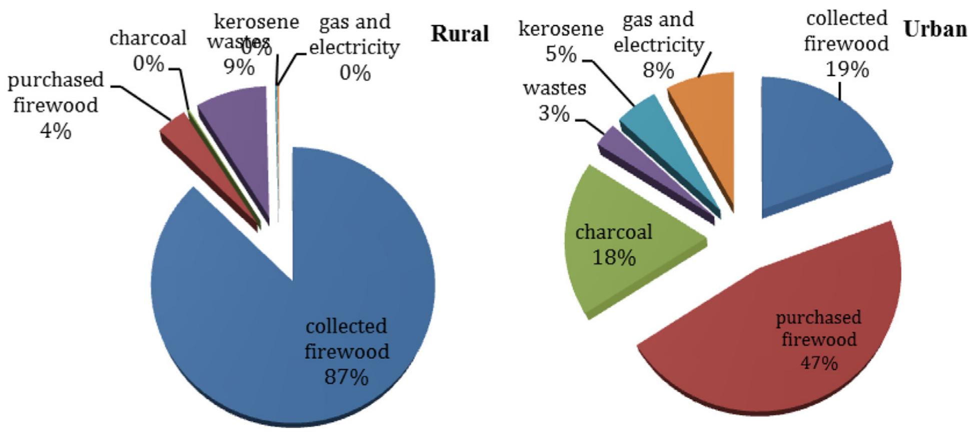

Fig. 2. The proportion of rural and urban households fuel sources for cooking in 2011 [17].

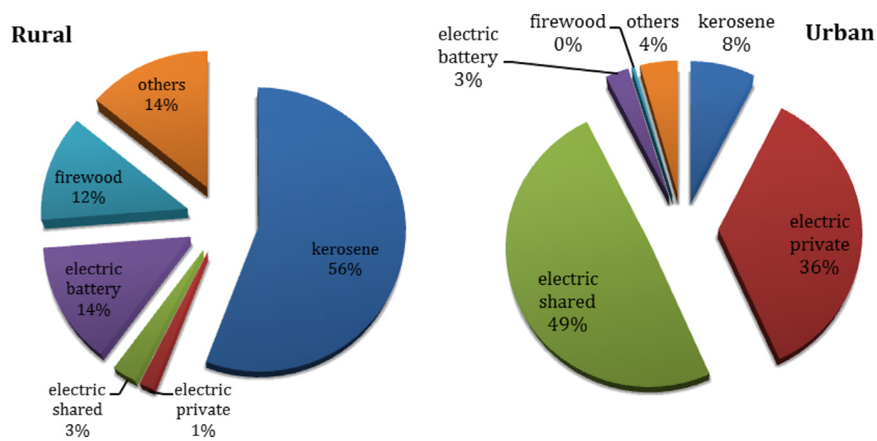

Fig. 3. The proportion of households fuel sources for lighting in 2011 [17].

Table 2
Ethiopian electrical energy production capacity by fuel sources in 2012 [14].

	Capacity (MW)	Generation (TWh/year)	% Share of total
Hydro	1950	6.2	99.2
Diesel	130	0.01	0.2
Wind	80	0.03	0.5
Geothermal	7	0.01	0.1
Total	2167	6.3	100.0

equivalent to 2 MWh useful energy that is delivered to food for cooking. About 90% of the biomass is used among households without conversion, whereas the rest is converted to charcoal and biofuel. About 0.6% of the biomass is used in the commercial sector and 0.1% is used for transportation being converted to biofuel. The non-commercial energy from biomass accounts for more than 98% of the overall household energy use. Biomass energy is perceived as a free commodity; as a consequence 95% of the rural and 20% of the urban households collect their biomass fuel from forests. The major energy need is for cooking. Fig. 2 shows rural and urban cooking energy consumption by fuel types. Nearly 100% of the rural and 90% of the urban uses biomass as a basic cooking fuel. In rural areas, about 14% of the households use biomass for lighting and 0.4% in urban areas. The national annual biomass energy use is estimated at about 70 million tons. This is between 4 and 5 t per households. Studies conducted in Ethiopia also show a range of 0.7–1 t per person per year [19,20]; this is about 3.5–5 t per household. This could be linked to the drastic forest loss of the country between 2005 and 2010, when 6% or 724,000 ha of the natural forests were lost [21].

2.1.2. Petroleum

Ethiopia is among the non-oil producing countries in the world. It is entirely dependent on imported oil. The national oil consumption is 25 TWh in 2009. Out of this, heavy oil accounts for 64% followed by 35% of light oil and the rest includes LPG and other petroleum products. About 81% of the petroleum is used for transportation, 13% and 6% is used in residential and industrial sectors respectively. Petroleum accounts for 99.8% of the transportation fuel, where the rest comes from biofuel. About 37% of the light petroleum products and all LPG are used by households, where the rest light petroleum is used for transportation. About 5% of the urban and 0.2% of the rural population uses kerosene for cooking. Rural and urban light energy use is presented in Fig. 3. Kerosene is mostly used for lighting; about 8% of the urban and 64% of the rural uses it. The amount of kerosene used for lighting is unknown in Ethiopia, since kerosene is also used for cooking. Studies show that, a single kerosene wick lamp in developing countries consumes 36–70 l of kerosene per year [22], the same may apply to Ethiopia. In 2009, about 280 million liters of petroleum products were used for household services in Ethiopia [23].

2.1.3. Electricity

The Ethiopian electricity production scheme is categorized as inter-connected system (ICS) and self-contained system (SCS) [14]. The ICS consists of 12 hydro, 11 diesel standby, one geothermal and 2 wind farms with an installed capacity of 1940 MW, 112 MW, 7.3 MW and 81 MW respectively, totaling 2140.3 MW. The SCS consists of 20.65 MW from diesel and 6.15 MW of small hydro [14]. Table 2 presents the country's electrical energy by sources. Electricity production from hydro accounts for 99% of the total electricity

production, followed by wind for 0.5%. Only 0.2% of the total electricity generation comes from non-renewable sources, almost all the production is from renewables. The totally produced electricity only accounts for 2% of the overall primary energy consumption. Households and industry are the main consumers of electrical energy, sharing 40% each followed by commercial areas by 20%. Only 2% of the population or 1.7 million people are connected to electricity. There are huge differences between urban and rural households in electrical energy consumption as shown in Figs. 2 and 3 [17]. About 8% of the urban and almost none of the rural households used electricity for cooking and about 87% of the urban and 5% of the rural households used electricity for lighting. This is a clear manifestation of the rural energy poverty requiring urgent and careful planning to sustainably alleviate their problems.

2.2. Policy plan on electrical energy production

Policy can be a tool by which resources are used to solve certain societal problems, but it is not always consistent with the priority problems to be addressed. In this section, the policy plan of the country is presented to indicate how the studied renewable energy sources are considered in present and future national and households' energy systems. The overall development plan driven by a particular energy policy provides an insight to what extent the rural energy issue is considered.

Until the year 2000, the Ethiopian electrical energy generation was below 2 TWh per year [15]. Since 2000, it has started to increase due to newly installed hydroelectric power plants. Within ten years the installed capacity and its associated electricity generation grew threefold, during which the total generation increased to 6 TWh in 2012 [14]. Hydro, wind, geothermal and oil are the main energy sources. Among these, hydro dominates the total electricity generation by more than 99%, and continues to dominate. According to the growth and transformation plan of the country for 2015 [24], the present generation is planned to grow fivefold to 30 TWh. Two hydro projects, the Grand Renaissance dam on the Blue Nile and the Gibe III dam with a designated power capacity of 8000 MW are already under construction to achieve the plan. Another five hydropower stations ranging from 250 MW to 400 MW from Chemoga Yeda, Geba, Halele Werabesa and Genale Dawa III and IV with a total installed capacity of 1500 MW are already under preparation. In addition, since 2012 two new wind farms with the installed capacity of 81 MW were introduced as an option for the shortfall of hydroelectric power during the dry season. Electricity production from wind is also expected to be increased to 866 MW. According to different data sources including the national databases, solar is not yet harnessed and only 150,000 solar home system (SHS) are planned to be distributed to rural areas and institutions [24]. A universal energy access program is also included in the plan, when the electricity distribution line is expected to be doubled from its current 130 thousand kilometers to increase the number of consumers from two to four million. Between 2005 and 2011, 2.7 million improved biomass stoves have been distributed and an additional 9 million units are planned. About 3 million solar cookers, 65 microhydropower plants and 26,000 biogas plants are also part of the plan to be implemented.

3. Methodology

3.1. Data and general approach

Energy can be obtained from various sources; solar, wind and hydro are most widely studied and applied, and therefore studied in this paper as well. Their quantification is made in three types of potentials: theoretical, geographical and suitable [7,8,25,26]. This approach is adapted for the current study to assess the potentials and analyze its situation in the country. The theoretical potential refers to the average amount of energy obtained from a total physical unit. The geographic potential is the fraction of theoretical potential reduced due to geographic constraints. The suitable potential represents the minimum amount of physical units that can allow renewable energy installations. Suitability for stand-alone estimations additionally considers the feasibility of these energy sources to install at households.

The estimation was conducted by combining different data and literature information. Data for solar and wind energy was obtained SWERA and NASA atmospheric science databases [27,28]. The Solar and Wind Energy Resource Assessment (SWERA) is a project sponsored by the Global Environment Facility (GEF) and administered by UNEP. This project aims at developing information tools to stimulate renewable energy development. SWERA produced a range of solar and wind datasets and maps at better spatial scales of resolution than previously available. This work relied on satellite and terrestrial measurements, numerical models, and empirical and analytical mapping methods. The SWERA Renewable energy Resource Explorer (RREX) is an online Geographic Information System (GIS) tool for viewing renewable energy resource data through which the current data on wind and solar energy resources were retrieved. The data from SWERA was combined with NASA wind and solar energy data obtained from atmospheric databases based on the longitudinal and latitudinal location of the areas of the country. Categorized land area for wind density as well as hydro data were obtained from the available literature and Ethiopian ministry of water and energy databases [24,29]. The estimation for solar and wind energy production potential is made based on the annual energy density in KWh/m^2 derived from the data presented in Figs. 5 and 7. Flow rate and basin elevation for hydro is based on [29], as presented in Table 4. Specific methods used in the estimations are presented in Sections 3.2–3.4 below.

3.2. Data procedure for solar energy

Solar energy could be directly converted into electric energy in photovoltaic (PV) cells, concentrating solar power (CSP) and solar thermal collectors for heating and cooling (SHC). PV is among the most used solar energy technologies chosen for the present estimation. It is a method of generating electric energy by converting solar radiation into direct current electricity using solar panels composed of a number of solar cells containing semi-conductor compounds. The solar PV system is the most flexible power system that could be directly connected to the grid or standalone as a solar home system (SHS). We estimated both applications by designating land for large scale and rooftop for standalone. The average solar irradiation is determined based on the Fig. 4 containing data from 19 randomly selected locations in the country. Fig. 4 shows monthly averaged daily horizontal irradiation from randomly selected areas in the country. As shown in the data, Ethiopia receives varying solar irradiation ranging from 4.5 KWh/m^2 to 7.5 KWh/m^2 per day. The minimum irradiation is received during the summer months in highland areas. Areas with irradiation exceeding 7.5 KWh/m^2 per day are in the extreme north down to the eastern border to the southern rift valley regions. Fig. 5 presents the country's solar radiation patterns on a map. In average Ethiopia receives about 6.0 KWh/m^2/day, equivalent to 2200 KWh/m^2 per year.

The theoretical solar energy production potential of the country is determined based on the average annual solar radiation derived from Fig. 4 and land resources data from FAO statistics [30]. The annual electric energy production potential (E_s) is calculated from the annual average solar irradiation per square meter (I_s), PV system efficiency (η) and assumed areas for PV

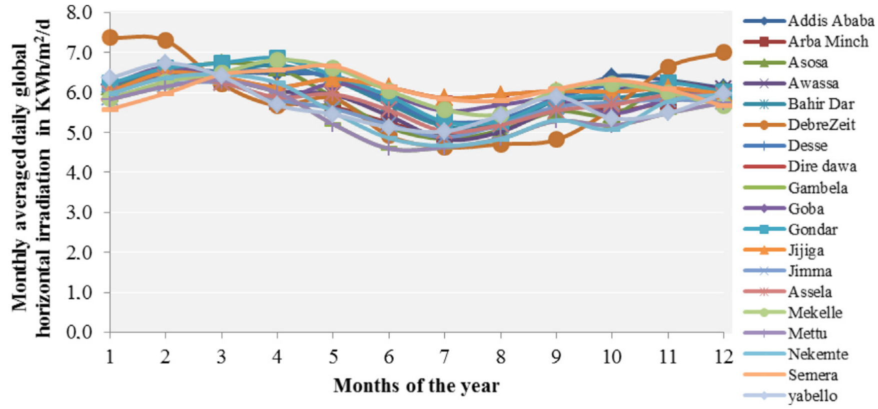

Fig. 4. Monthly averaged daily global horizontal irradiation pattern in Ethiopia in 2012 [28].

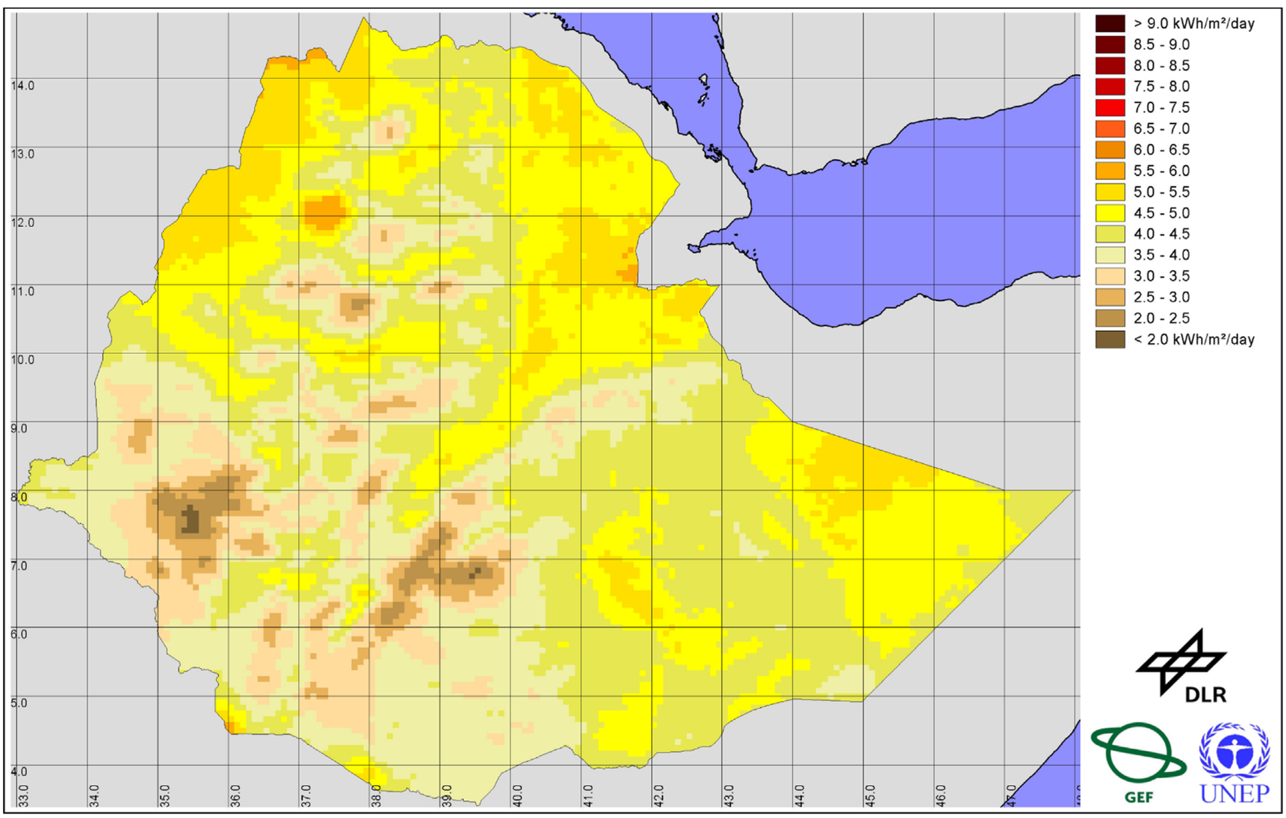

Fig. 5. Annual average daily total sum of DNI in kWh/m²/day for Ethiopia [35].

installation (A) as $E_s = I_s \eta A$ [31,32]. This paper assumes an annual irradiation of 2200 KWh/m^2 based on the average values in Fig. 4 and assumed PV system efficiency of 12% [33]. Based on this information we estimated an annual theoretical potential without making any areal restrictions. However, it is impossible to cover all land areas with PV; therefore, an adjustment is made by excluding forest, agricultural and built lands. Unused and pasture land accounting for 72% of the land areas [30] is estimated for its large scale geographic potential, whereas rooftops from residential areas are for standalone based on [7]. Only rooftop areas from residential areas are considered due to unavailability of data on other rooftop areas. The available rooftop area is estimated based on the work of Hoogwijk [34] by introducing roofing coefficient (the ratio of housing unit per household) which is nearly 0.9 for Ethiopia. Due to certain restrictions based on [18], we determined 4% of the land and 40% of the rooftop to be suitable for solar energy production.

3.3. Data procedure for wind energy

The Ethiopian wind energy potential varies from location to location. In Fig. 6 the monthly averaged daily wind energy generation pattern of the country from 19 randomly selected locations are presented. According to the global wind energy classification [36], the average Ethiopian wind energy is classified as class 1. Only a few areas are within good to excellent (above class 4) wind energy categories. Areas with good and above wind energy categories are primarily located in the highland areas along the Great Rift Valley extending to the northern parts of the country. The annual average wind energy intensity is determined based on the monthly averaged daily estimated energy densities presented in Fig. 6. The annual average of 360 KWh/m^2 is estimated from the monthly averaged daily wind energy data corresponding to wind speed class of 3.5–5.6 m/s. This class is considered as a wind speed cut-in to move wind turbine, and a

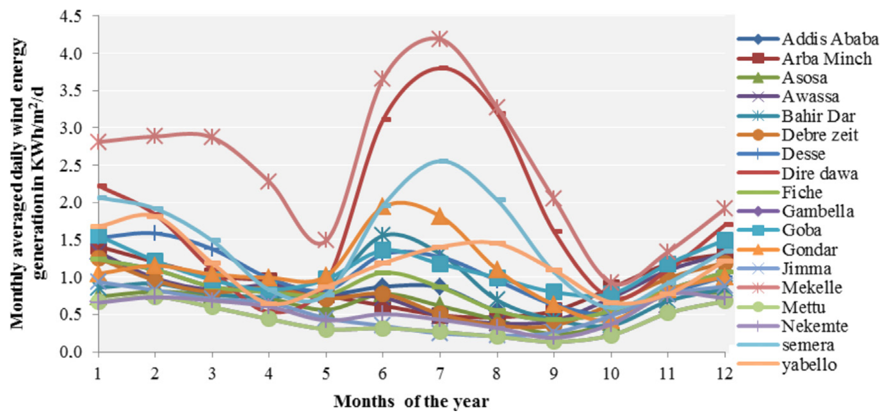

Fig. 6. Monthly averaged daily wind energy generation pattern in Ethiopia in 2012 [28].

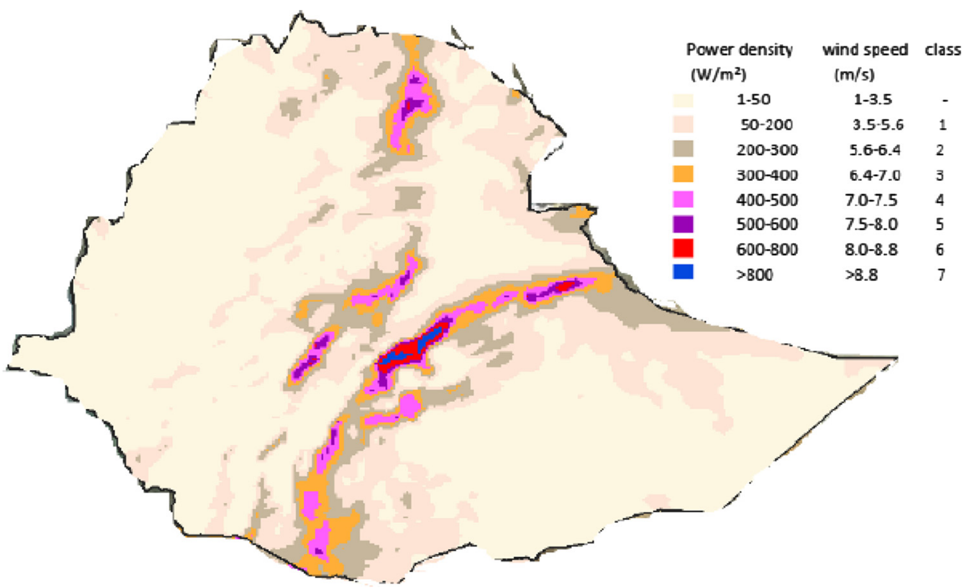

Fig. 7. Map of Ethiopian wind energy resources [28].

wind speed less than this is not considered in wind energy classification. In Fig. 7 the country's map with wind energy pattern is presented. As shown in this figure, the Ethiopian overall wind energy is categorized as class 1, which is economically less competitive for the current large scale wind turbine application. Due to this, the power output from standalone is less likely to provide the amount of energy required for households, with the exception of a few areas with a promising potential for large scale applications. Hence, no small scale analysis is done since major areas of the country are not suitable for wind energy installations.

The wind power density (P) of a turbine swept area (πr^2) is calculated from the density of moving air (ρ) and third power of prevailing wind speed (v), as $P=0.5\rho\pi r^2 v^3$ [37]. This value is multiplied by 8760 h to estimate an annual energy (E_a) generation per square meter. An annual energy generation (E_t) from an assumed area (A) is estimated by introducing turbine efficiency (η): $E_t=E_a\eta A$. In current paper a turbine efficiency of 0.3 and air density of 1.263 kg/m^3 is considered based on the information from [37,38]. The electric output of the turbine is proportional to the size of wind turbine and its hub, but wind power density depends on the wind speed. The power density over a turbine swept area determines the power output of that particular turbine. As stated in the formula, the power in a wind at a certain location is equal to the density of moving air times third power of its speed, each doubling of wind speed corresponds to an increase of its power density by eight times. But all areas are not suitable to install wind turbine. Hence agricultural, forested and built up lands are excluded, only pasture and unused land are assumed to be geographically available for wind energy development. Wind turbine installation is further restricted by local infrastructure, altitude, population and distance from main power, environmental constraints like nature reserves and protected areas [39]. Since specific data regarding these factors is not available in Ethiopia, we decided to use the estimated suitability factor for eastern Africa [39] by considering the geographic setup, infrastructural development and general wind speed pattern of the country.

3.4. Data procedure for hydro energy

Ethiopia has mountainous areas with many small rivers convenient for small hydroelectric power. The first hydroelectric power was introduced in Ethiopia in 1940, with a progressive propagation to different parts of the country. In addition, a survey conducted since the late 1980s has identified about 200 small scale potential sites across the main river basins [40]. Small hydroelectric power is of two types; run-of-river and reservoir [41]. The type built in Ethiopia was mostly run-of-river, which depends on the amount of running water. However, most of those plants are abandoned due to

the introduction of a more reliable conventional grid system. The possibility to install such type of hydroelectric power plants relies on the level of precipitation to maintain the level of water in a bank. At present only three micro-hydroelectric power schemes are functional with a total installed capacity of 6.15 MW [14]. Due to this and other reasons related to data, the estimation for small scale potential was not performed.

All Ethiopian major river basins run-off the central highlands in all directions, but only eight of them are characterized for their hydroelectric production potentials. First we made an estimation of the theoretical potential of each river basin from their respective flow rate and elevation. The power (P) produced at the turbine is $P=\eta\rho gQh$ [42] and energy (E) output of the turbine in (Wh) is estimated as $E=Pt$; where, η refers to efficiency of the turbine, ρ density of the water in (kg/m^3), g acceleration of the water due to gravity (m/s^2), Q water flow rate (m^3/s), h is effective head pressure at turbine (m) and t is hours in a year. Uncertainty in weather conditions and intermittent drought over the region has been considered for the estimation of dependable ratio that determines its system efficiency. However, actual production requires suitable areas to construct dams. Suitability for dam construction involves certain environmental factors related to local natural resources, social and economic issues. Suitability data for Ethiopia is not available, but a factor 0.5 was adapted based on the suggestion of [43].

4. Results

4.1. Potential of solar energy

Table 3 presents the solar energy potential of the country. The annual solar radiation arriving on the country's land area provides a theoretical potential of about 260 PWh. All this energy is not harvestable due to certain restrictions. Accordingly, we estimated an annual geographic potential of 192 PWh from land and 0.1 PWh from rooftop areas. However, all these areas are not suitable to install PV, because of geographic and environmental constraints. Thus, only 7 PWh for large scale and 0.04 PWh for standalone are estimated as suitable solar energy potential applications. The estimation made for rooftop area could be considered as small, because of the better suitability of rooftops from institutions and industries buildings. Rooftops from institutions and industries buildings are relatively often made from strong roofing materials and easy to connect to the national grid, but is not included due to lack of data. The suitable potential from rooftop area for standalone application is about 7 times of the present electricity production of the country while the suitable potential from land for large scale application is more than 1000 times.

Table 3
Grid and standalone electrical energy production potentials from solar.

Potentials	Large scale		Standalone		Total	
	Land area (10^3 km^2)	Energy (PWh/year)	Rooftop area (10^3 km^2)	Energy (PWh/year)	Area (10^3 km^2)	Energy (PWh/year)
Theoretical	1000	264	–	–	1,000	264
Geographic	726	192	0.4	0.1	726	192.1
Suitable	28	7	0.1	0.04	28	7.1

Table 4
Ethiopian electrical energy production potential from wind.

Type of potential	Area in 10^3 square kilometers	Annual wind energy production potential in PWh
Theoretical	1000	110
Geographical	720	79
Suitable	36	4

4.2. Potential of wind energy

The country's wind energy potential is shown in Table 4. The estimated annual theoretical potential of 110 PWh is based on the total land area and annual average wind energy generation per square meter without restriction. However, it is impossible to install wind turbine in all areas, hence agricultural, forested and built up lands are excluded. About 80 PWh is estimated as geographic potential from pasture and unused lands. Wind turbine installation is further restricted by a number of factors; hence only 4 PWh is estimated as annual suitable wind energy potential. However, the suitable potential for large scale application is more than 600 times of the present electricity production of the country.

4.3. Potential of hydro energy

All the major river basins pour-off the central highlands in all directions contributing from western to Blue Nile and from south to Indian Ocean crossing some East African countries. That could be the reason why Ethiopia ironically called the “water tower of East African countries”. Out of 11 major river basins 8 of them are identified for their hydro energy production potentials. In Table 5 data on flow rate and elevation and the respective energy potential of main river basins in the country is presented. The annual theoretical hydro energy potential of the country was estimated at 954 TWh, out of which its geographic potential is 286 TWh. About half of this is suitable for large scale application, which is about 24 times of the present electricity production of the country. Abbay (Blue Nile), Omo-Ghibe and Baro Akobo are the

Table 5
Ethiopian annual hydroelectric generation potential.

River basin	Flow rate (m^3/s)[a]	Elevation (m)[a]	Annual electric energy production potential in TWh (10^{12} Wh)		
			Theoretical	Geographical	Suitable
Abbay	1738	3761	449	135	67
Awash	155	3985	43	13	6
Baro Akobo	748	2854	147	44	22
Genale Dawa	186	4214	54	16	8
Omo Ghibe	526	3260	118	35	18
Rift-Valley	178	3720	45	14	7
Tekeze	260	3981	71	21	11
Wabi Shebele	100	3998	28	8	4
Total	3892	3722	954	286	143

[a] *Source* [29].

Table 6
The contribution of renewable energy to the Ethiopian electric energy production.

	Present use (TWh/year)	Per capita (kWh/year)	2015 plan (TWh/year)	Potential (PWh/year)	Per capita if used (MWh/year)	% Used and planned
Solar	0.0	0.0	0.0	7.5	90	0.0
Wind	0.03	0.4	3.3	4	48	0.1
Hydro	6.2	75	29.0	0.2	1.7	24.6
Total	6.23	75.4	32.3	11.7	139.7	0.33

three major river basins covering about 80% of the hydroelectric power potential of the country.

5. Discussions

5.1. Contribution of renewable energy to large and stand-alone energy systems

As understood from the data, energy system in developing country is different from western countries. The contribution of renewable energy in western countries is evaluated based on its proportion in grid systems. In developing countries the contributions for both grid and standalone applications are essential, because of the large proportion of the population residing in remote areas unconnected to the grid.

5.1.1. Contribution to current and planned grid system

In Table 5 the country's electrical energy production potential from solar, wind and hydro is presented. The country's energy production potential from solar, wind and hydro is 7 PWh, 4 PWh and 0.1 PWh respectively. The potentials presented here refer to the suitable potential supposed to be harvestable. Solar energy accounts for 58% followed by wind 40% and hydro accounts for only 2%. By the year 2012, the Ethiopian renewable electric energy production was 6 TWh, which is 0.05% of the available potentials. As presented in Table 2, about 99% of this production is derived from hydro and the rest is from wind, geothermal and diesel. Ethiopia is among developing countries focusing on large scale power plant developments setting a target for 2015 as “growth and transformation plan” [24]. In Table 6, the country's renewable energy potential contribution to present use and future plan is presented. During the next years, the present electrical energy generation will be increased by five-folds to over 30 TWh, corresponding to 0.33% of the available potential (Table 6). Out of this, hydro accounts for 29 TWh followed by 3 TWh from wind. The potential for solar is over 230 times larger than that of the overall plan, which is about 90 MWh per capita per year. However, none of the potential has yet been harnessed but also insufficiently considered in the power plan of the year 2015. The present national annual per capita consumption is 75 kWh and is expected to increase to 390 kWh if the power plants projects turn out to be successful.

Two issues need to be emphasized: the reason why hydro is mostly favored and its contribution to the overall energy system. This can be discussed from a technical point of view and with respect to accessibility. Hydroelectric power has a technical efficiency of up to 90% and its technology is well advanced relative to solar PV and wind turbine [38]. The energy density from hydro is more than the other two. For instances, one cubic meter of water dropping from 10 m high theoretically provides about 100 kWh, whereas a solar energy arriving on a square meter area supply about 6 kWh. In addition, depending upon the weather condition, hydro can be operated for longer hours than solar and wind. Compared to solar, wind has a better efficiency and generation time, but less than that of hydro. The systemic energy loss from hydro is predictable which can be compensated from its back-up system, whereas both solar and wind are subject to weather conditions, and their power output is intermittent and cannot be systematically regulated. However, they can supplement each other and contribute to resolve power shortages especially during the dry season when hydro is reduced [6]. The second point is the issue of accessibility. It is obvious that electric energy is essential for economic development and societal wellbeing [1,44]. The huge production as stated in the plan can contribute to overall economic development, since it may motivate investors and excess energy can be exported. This is what the plan is meant for and focused to transform the agrarian economy to an industrial economy for which energy is the main driving forces. A certain amount of energy is expected to be exported to neighboring countries such as Kenya, Sudan, Djibouti and in the long run to Egypt and Yemen. Its potential economic benefit to the national overall economic growth is large. In contrast, large proportions of the population living in rural areas have no access to the grid due to economic, infrastructure and settlement problems; and connecting them in near future is less likely. This implies that the direct contribution of the current and planned large scale power development to solve the rural energy problems is likely to be small.

5.1.2. Contribution to standalone

In Ethiopia more than 95% of the households depend on biomass energy for cooking. The overall annual household biomass energy use in traditional stoves is equivalents to about 20,000 kWh (i.e. in the form of heat energy where only 10% is used, which is about 2,000 kWh), whereas the power output from a square meter of solar PV panel is 265 kWh (based on 12% solar PV conversion efficiency). The power output from the solar PV panel depends on the PV's solar energy conversion efficiency and local irradiation implying that a large solar PV size is required to produce the amount of energy required for cooking. Based on this, if PV is considered to provide cooking energy instead of biomass, about 8 m^2 solar PV panel is needed for an average household. This amount is inconceivable to install in rural areas. The energy required for lighting is relatively small, households in rural areas mostly depend on a single wick kerosene lamp or candle. If households use three compact fluorescent lamp (CFL) of 10 W for 5 h per day, their annual consumption is only 55 kWh, which can be met by 0.2 m^2 solar PV panel. Therefore, currently available solar PV can provide rural light energy services but is less likely to solve the main energy need for cooking, because of its low solar energy conversion efficiency.

The power output from wind turbines is influenced by the prevailing wind speed, rotary diameter, turbine height and local terrain. As shown in the data, the Ethiopian overall wind speed is classified as class 1, with annual average energy generation of 110 kWh/m^2 (at 30% turbine efficiency). As shown in Fig. 6, major areas across the country have a wind speed pattern less than the cut-in wind speed to move wind turbine with the exception of few areas with good to excellent wind speed. Therefore, it is unlikely that standalone wind turbines provide sufficient energy for rural households.

Small hydro has a range of efficiency between 60% and 80% [45], which is about three times larger than the efficiency of a wind turbine. Most of these hydroelectric systems are run-of-river types that do not need the construction of a reservoir or a dam. They operate on naturally running water. A typical small hydropower plant with a flow rate of 0.01 m^3/s (just small river) and 10 m head can generate an annual electrical energy output of 5,000 kWh. Due to the absence of a back-up system, small hydropower plants of such type are highly vulnerable to changing weather conditions and they often suffer from power outages, and are less likely to provide the amount of energy required. In addition, the availability of river water is not like solar or a blowing wind arriving directly at each house. Hydro requires a transmission line that brings its electrical energy to each house. Based on this analysis, it can be concluded that, the standalone system from hydro is less likely to be important in areas having low precipitation, intermittent drought and sparsely inhabited households. Small scale hydro plants with storage system or reliable flow rate can provide better alternative to areas of small villages or towns inaccessible to central power stations.

In general, this study used average data and general assumptions, and may not reflect the actual potential to be harvested. Specific data at specific areas is required for particular applications. Values obtained here reflects the general patterns of the country's energy profile, and the level at which renewable energy is contributing relative to its potential. Ethiopia is among the top five Sub-Saharan African countries such as Nigeria, Ethiopia, Democratic Republic of Congo, Tanzania and Kenya housing more than 45% of the sub-Saharan African population without access to electricity. Out of 652 million relying on traditional biomass energy for cooking in sub-Saharan Africa, 317 million live in these five countries [4]. Therefore, the situation in Ethiopia is typical for other developing countries.

6. Conclusion

The analysis shows a large variation between rural and urban modern energy consumption. Biomass is the dominant energy source used for cooking by both poor urban and rural households. The household's energy use for cooking is ten times as large as the household's use in western countries. Kerosene is the main energy source used in rural areas for lighting, while electricity is used in about 90% of the urban areas. The countries' renewable energy from solar, wind and hydro can supply enough energy to fulfill the demand. These renewable energy sources generate electricity, which is not appropriate for cooking food, since electric cooking appliances are expensive in rural areas. However, they can fulfill energy needs at national scales, although they are not suitable for fulfilling energy needs in rural areas except lighting and powering of electronic devices. Therefore existing western solutions with respect to renewable energy supply systems do not solve energy problems in developing countries. This shows the strong need for solving the energy need for cooking based on the local situations.

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References

[1] Kaygusuz K. Energy for sustainable development: a case of developing countries. Renew Sustain Energy Rev 2012;16(2):1116–26.
[2] Fouquet R, Pearson PJG. Past and prospective energy transitions: insights from history. Energy Policy 2012;50(0):1–7.
[3] Pachauri RK, Reisinger A., Climate change 2007. Synthesis report. Contribution of Working Groups I, II and III to the fourth assessment report. Switzerland: IPCC, Geneva (Switzerland); Intergovernmental Panel on Climate Change, Geneva (Switzerland); 2008. 104 p.
[4] OECD/IEA. Energy for all: financing access for the poor, in World Energy Outlook. Paris: International Energy Agency; 2011.
[5] Adam Brown SM, Dobrotková Zuzana. Renewable energy markets and prospects by technology. Information paper. Paris: Energy Agency; 2011.
[6] Delucchi MA, Jacobson MZ. Providing all global energy with wind, water, and solar power, Part II: reliability, system and transmission costs, and policies. Energy Policy 2011;39(3):1170–90.
[7] Hoogwijk MM. On the global and regional potential of renewable energy sources. Universiteit Utrecht, Faculteit Scheikunde; 2004, http://dspace.library.uu.nl/handle/1874/782.
[8] Mondal MAH, Denich M. Assessment of renewable energy resources potential for electricity generation in Bangladesh. Renew Sustain Energy Rev 2010;14 (8):2401–13.
[9] Bekele G, Palm B. Wind energy potential assessment at four typical locations in Ethiopia. Appl Energy 2009;86(3):388–96.
[10] Mulugetta Y, Drake F. Assessment of solar and wind energy resources in Ethiopia. II. Wind energy. Sol Energy 1996;57(4):323–34.
[11] Bekele G, Palm B. Feasibility study for a standalone solar–wind-based hybrid energy system for application in Ethiopia. Appl Energy 2010;87(2):487–95.
[12] Bekele G, Tadesse G. Feasibility study of small hydro/PV/wind hybrid system for off-grid rural electrification in Ethiopia. Appl Energy 2012;97(0):5–15.
[13] Bank W. World development indicator. World Bank; 2013.
[14] EEPCo. Ethiopian Electric Power corporation in Ethiopian Electric Power corporation; 2012.
[15] IEA. Country energy statistics in IEA databases; 2011.
[16] MoWE. Energy balance and statistics of Ethiopia, in Ministry of water and energy databases. Addis Ababa; 2011.
[17] CSA. Ethiopian welfare monitoring survey 2011. Addis Ababa: Ethiopian Central Statistical Agency; Addis Ababa.
[18] Bhattacharya SC, Salam P Abdul. Low greenhouse gas biomass options for cooking in the developing countries. Biomass Bioenergy 2002;22(4):305–17.
[19] Ameha A. Sustainable supply of wood resources from Adaba-Dodola Forest Priority Area. In: Paper Presented on the Alumni Seminar Addis Ababa University; 2002.
[20] Bewket W. Household level tree planting and its implications for environmental management in the northwestern highlands of Ethiopia: a case study in the Chemoga watershed, Blue Nile basin. Land Degrad Dev 2003;14(4): 377–88.
[21] FAO. Global forest resources assessment country report. In: Global forest resources assessment. Food and Agricultural Organization of the United Nations; 2010.
[22] Mills E. The specter of fuel-based lighting. Science 2005;308(5726):1263–4.
[23] MoWE. Ethiopian energy balance statistics. Addis Ababa: Ministry of Water and Energy of Ethiopia; 2011.
[24] MoWE. Ethiopian master power plan for 2015. Addis Ababa: Ministry of Water Resources and Energy; 2011.
[25] Angelis-Dimakis A, Biberacher M, Dominguez J, Fiorese G, Gadocha S, Gnansounou E, et al. Methods and tools to evaluate the availability of renewable energy sources. Renew Sustain Energy Rev 2011;15(2):1182–200.
[26] Moriarty P, Honnery D. What is the global potential for renewable energy? Renew Sustain Energy Rev 2012;16(1):244–52.
[27] NASA. Atmospheric sciences data center, surface meteorology and solar energy; 2011.
[28] SWERA. Solar and wind resources assessment. In: United Nation Environmental program; 2012.
[29] Awulachew SB, Yilma AD, loulseged M, Loiskandl W, Ayana M, Alamirew T. Water resources and irrigation development in Ethiopia, vol. 123. IWMI; 2007.
[30] FAO. Country land resources data. FAOSTAT; 2012.
[31] Hofierka J, Kaňuk J. Assessment of photovoltaic potential in urban areas using open-source solar radiation tools. Renew Energy 2009;34(10):2206–14.
[32] Wiginton L, Nguyen H, Pearce J. Quantifying rooftop solar photovoltaic potential for regional renewable energy policy. Comput Environ Urban Syst 2010;34(4):345–57.
[33] OECD/IEA. Technology roadmap: solar photovoltaic energy. International Energy Agency; 2010.
[34] Hoogwijk MM. On the global and regional potential of renewable energy sources. Utrecht: Universiteit Utrecht; 2004.
[35] Schillings Christoph, Meyer Richard, Franz Trieb. Solar and wind energy resource assessment; high resolution solar radiation assessment for Ethiopia. UNEP/GEF; 2004.
[36] Ilinca A. Wind potential assessment of Quebec Province. Renew Energy 2003;28(12):1881–97.
[37] Şahin AD. Progress and recent trends in wind energy. Prog Energy Combust Sci 2004;30(5):501–43.
[38] Evans A, Strezov V, Evans TJ. Assessment of sustainability indicators for renewable energy technologies. Renew Sustain Energy Rev 2009;13(5): 1082–8.
[39] Hoogwijk M, de Vries B, Turkenburg W. Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. Energy Econ 2004;26(5):889–919.
[40] Hailu SS. Hydropower of Ethiopia: status, potential and prospects. EACE Bull 1998;1:1.
[41] IEA. Technology roadmap: hydropower. Paris: International Energy Agency; 2012.
[42] Purohit P. Small hydro power projects under clean development mechanism in India: a preliminary assessment. Energy Policy 2008;36(6):2000–15.
[43] Conner AM, Francfort JE, Rinehart BN. US hydropower resource assessment: final report. US Department of Energy, Idaho Operations Office; 1998.
[44] Kaygusuz K. Energy services and energy poverty for sustainable rural development. Renew Sustain Energy Rev 2011;15(2):936–47.
[45] Paish O. Small hydro power: technology and current status. Renew Sustain Energy Rev 2002;6(6):537–56.